

# A new concept of a high-energy space-based cosmic ray telescope

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## Abstract

Cosmic ray science has proved to be a very active field, with several important results from recent space-based instruments. Next generation experiments will explore the multi-TeV energy range, trying to cope with the mass and power budget constraints of artificial satellites that limits the collecting area thus reducing the available statistics at the highest energy. With the aim to improve the compromise between area and mass, we propose a new concept for a cosmic-ray telescope in which the detector elements are organized in bars along the 3 axis. In this way we can also maintain a good event shower sampling (for direction and energy reconstruction) and a relatively small number of channels (required power) as the detector size increases. A possible implementation of the concept is also evaluated with a Geant4 simulation.

**Keywords:** Cosmic rays, Calorimeter, Space-based

## 1. Introduction

The high-energy cosmic ray field has grown significantly in recent years. This generation of space-based detectors, like Pamela [1], AMS-02 [2] and Fermi-LAT [3], provided new, unexpected results that, while increasing significantly our knowledge of characteristics of primary cosmic rays, posed also new questions. As an example, diffusive propagation models, that work nicely for most of the observed spectrum, are considered less reliable above few TeV where we expect to see effects of e.g. local sources. In particular, high-energy cosmic-ray electrons and positrons radiate energy very quickly and carry information only of the nearby part of our Galaxy. Their spectrum and, possibly, their anisotropy in incoming direction, can lead to the discovery of acceleration sources, but high statistic measurement at energy above 1 TeV are required. Hints of dark matter are expected to be seen in  $\gamma$ -rays and cosmic rays, but current uncertainty on the astrophysical component (that can be considered as background in such searches) is one of the main limitation. New measurements in an extended energy range with larger statistics and smaller uncertainty are thus mandatory.

The next generation of detectors are trying to answer all these question by improving the measurement capability in the few TeV range, where the performance of the current detectors are limited. Recently launched instrument like CALET [4] or DAMPE [5] chose to have a very deep calorimeter. The good energy resolution is achieved at the price of a smaller acceptance: the geometry factor is of the order of a  $0.2\text{--}0.3\text{ m}^2\text{ sr}$  for electrons, which has impact on the time needed to collect enough statistics above 1 TeV. On the contrary the Fermi-LAT, optimized for  $\gamma$ -ray in the  $1\text{--}100\text{ GeV}$  range, made the opposite

choice with a large geometry factor of the order of  $2\text{ m}^2\text{ sr}$ , but with a worse energy resolution at 1 TeV.

Magnetic spectrometers naturally suffer of a lower acceptance when compared to pure calorimetric experiments of the same mass. The magnetic system represents heavy passive material, and reduces the field of view. On the other hand such device is required to measure particle charge, in particular to separate positive to negative charge. If a good energy resolution for hadron is required, magnetic spectrometer can use particle curvature for momentum measurement, but this technique works best at lower energy and optimization in the multi TeV is very demanding in terms of mass, power and size.

A calorimeter concept has been recently proposed to have an acceptance of  $\sim 3\text{ m}^2\text{ sr}$  to collect enough statistics in a reasonable time to explore the multi-TeV region [6]. The idea is to build a cubic calorimeter made of small cubic sensitive elements in order to have a 3D, deep, homogeneous and isotropic calorimeter. The large acceptance is achieved by accepting events from 5 out of 6 surfaces, while the last one is used for mechanical and electrical interfaces. The cubic element is usually a scintillating crystal, with the size of the order of the Molière radius for good shower sampling. The R&D on this kind of detector is well advanced.

While this idea is certainly interesting, this geometry requires some gaps between the modules for the routing of the readout cables and the mechanical structure. Moreover the number of channels is proportional to the volume of the detector, and scaling up its size means scaling also power consumption proportional to the volume. It is easier (cheaper) to put heavy satellites in orbit close to the Earth (Low Earth Orbits or LEO), therefore the solid Earth and its atmosphere can partially shield the detector field of view, as a result the gain of using 5 surfaces instead of 1 is partially reduced. As a reference the largest launch system currently available can put about 20 metric tons in LEO,

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but a few tons is currently considered a feasible size. As an example AMS-02 is about 7 tons and is probably the heaviest instrument currently operational.

In this work, we got inspired from the idea of the cubic and modular instrument, but modified a bit the geometry to try to limit the issues just described. The new concept will be fully described in section 2, while in the following one we show some calculation of the achievable acceptance and field of view, in particular in LEO. Finally in section 4 we will describe one possible implementation of the detector to prove that we can reach reasonable performance. Of course this work is not a full study of a complete detector design, but a proposal of a geometrical concept to be further refined in order to become a feasible and high-performance space-based cosmic-ray telescope.

## 2. The concept

The cosmic-ray telescope we are proposing is a pure calorimetric instrument, with emphasis on large collection area or, in other words, must be easily scalable to large volumes. A good energy resolution is of course important, but it is mainly given by the depth of the detector, which obviously scale with its size. However it must be capable to measure the energy of many type of cosmic rays: electrons, protons, alpha particles, etc. Granularity of the calorimeter is considered fundamental. It allows shower development imaging, for a better energy reconstruction and for particle identification. Particle incoming direction can be also measured, which is important for anisotropy searches. A good granularity usually implies a large number of channels, which in turn means large power consumption and event size. This can be a problem for very large detector if the number of channels is proportional to the volume.

The detector in this concept is a cube on side length  $L$ , with detector elements that are bars of the same length  $L$  and a much smaller side  $S$ . Each of the element is read from one side only, and provides information on energy deposition in the bar. The information of the position is given by the physical place of the bar itself, no information on longitudinal position (i.e. along the bar) is strictly required. The three dimensional sampling of the shower development inside the detector is given by arranging three sets of bars along the three coordinates  $x, y, z$ . The elements in one set of bars are arranged parallel one another in a  $n \times n$  grid, and spaced with a pitch that is twice their side; in this way there is enough empty space to combine the 3 sets in a single cubic shape. Figure 1 shows an example of this concept, using only 9 elements per side, while in a real detector the number of elements can increase arbitrary and the only constraint is that  $L = 2 \cdot S \cdot n$ . In figure 1 the readout system is shown with white cylinders, just to make clear that only 3 out of 6 sides are used to readout the full instrument. The other three, that we will call “active”, can be instrumented with other subsystems for precision tracking, charge  $Z$  measurements etc. To keep the active surfaces on the top of the full assembly the cube can be rotated to sits on one the corner. Of course the mechanical support structure must be designed to use the 3 non active surfaces and the rotated geometry, but the exact design of the mechanics is out of the scope of this work.

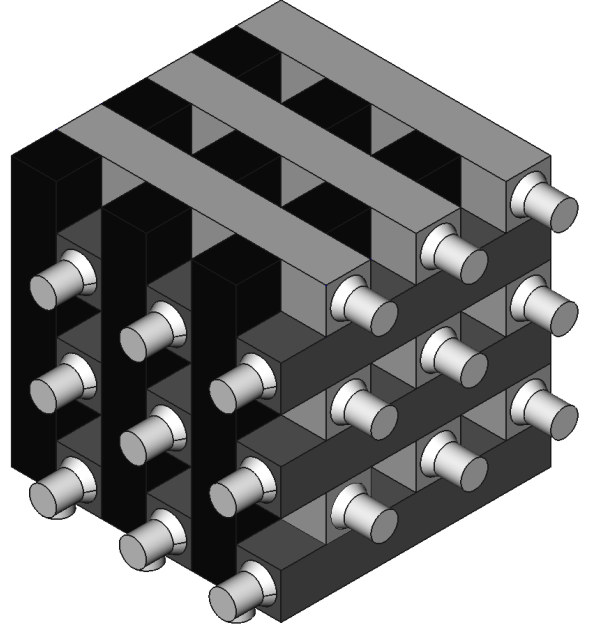


Figure 1: Graphical representation of the detector concept, here with only 9 bars per side. Different colors (gray level) are used for different bar orientations, while the white cylinders represent the readout devices.

No specific assumption on the detector element technology is done at this point. It can be either a homogeneous absorption system like an inorganic scintillator, or a sampling device with two or more materials. In section 4 we will abandon some generality and describe one specific case, as an example of the achievable performance. In the rest of this section we just want to highlight some of the pros and cons of this concept, in particular comparing it with the case of the “regular” cube that sits on one surface, and have the other 5 active.

As mentioned, scaling to large volume is a major drivers, and this design guaranties that while the volume increase with  $L^3$ , the number of channels is proportional only to  $L^2$ . This is a clear advantage with respect to a design in which the number of channels is proportional to the volume (i.e. increase faster than the acceptance when  $L$  increases). All the readout devices are on external surfaces (the 3 non active ones, possibly at the bottom and close to the spacecraft structure), simplifying the routing of the electrical connections. Moreover the detector pitch of  $2S$  leaves enough space for readout sensors and electronics.

In this design there is some empty space inside the calorimeter:  $1/4$  of the total volume is not instrumented. However this is not required for a space-based cosmic-ray telescope and, it allows for a larger volume (acceptance) if compared to a compact design with the same mass, since the average density is  $3/4$  of the detector material.

Particle showers are sampled in the 3 coordinates and it is possible to reconstruct shower direction and shape. In section 4 we will see how we can reach an angular resolution of few degrees. We mentioned that shower sampling can be used for leakage correction and quantify some kind of “quality” of

the energy measurement. However, if the calorimeter is deep enough, it can measure the energy via total absorption, and leakage correction with shower shape analysis is less important. It remains true that to fully exploit this geometry complex reconstruction algorithms can be required, for both direction, energy and shower topology.

### 3. Detector acceptance

A simple toy Monte Carlo simulation is used to evaluate the effective geometry factor, or acceptance, of the concept described in this work. Events are extracted from a surface of  $25 \text{ m}^2$  with isotropic direction distribution, and are propagated to detector represented by a cube of edge  $L$ . An event is considered good if it enters from one of the active surfaces and if it crosses more than  $L/2$  inside the detector volume. The latter cut mimics a minimum quality requirement, and tries to remove events that clips the edges of the detector. The exact cut in a real detector can be different, but in this simple exercise we don't want to go in such details.

We simulated different cubes of side  $L$  from 50 cm to 150 cm, for each case we consider both the “regular” cube, that sits on one surface (considered the only non active), and our “rotated” geometry in which the cube sits on a corner and only the top 3 surfaces are active. Moreover we consider the case of just the quality cut and with the additional request of accepting event with local zenith angle  $< 100^\circ$  to avoid events from the Earth Limb in case of satellite in LEO<sup>1</sup>. As for the quality cut, this one can be different from the actual cut of a real instrument (which depends the orbit, the angular resolution, etc), but is a reasonable representation of the reduction of field of view from the solid Earth.

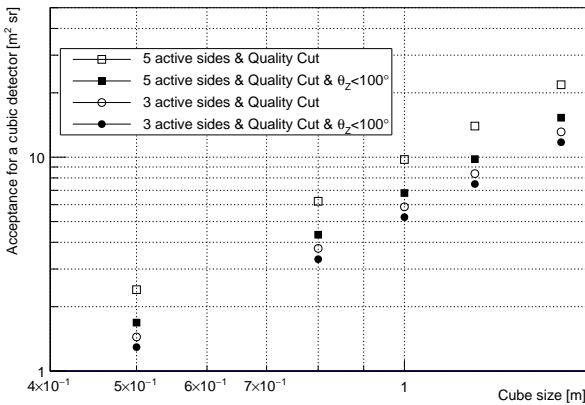


Figure 2: Acceptance for cubic detector with 3 and 5 active faces as function of cube side. Both case with simple cut and Earth-limited field of view are shown.

The acceptance is defined as the ratio between good and total generated events, normalized by area and solid angle. The

<sup>1</sup>See e.g. the discussion on Earth Limb in [http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT\\_caveats.html](http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html)

result of the simulation is presented in figure 2, where we can see that the acceptance increases as the square of the cube size, and that  $L \sim 1 \text{ m}$  is necessary to reach acceptance large enough for the multi TeV range. To have an idea on the corresponding mass of such a detector, we can assume an average density of a commonly used scintillator like CsI ( $4.5 \text{ g/cm}^3$ ) which leads to a reasonable mass of about 4 (8) metric tons at  $L=1 \text{ m}$  (1.2 m) while for the maximum  $L=1.5 \text{ m}$  considered here we obtain about 15 metric tons; not totally unfeasible, but pretty close to the limits.

The regular cube, with 5 active surfaces provides always superior acceptance than our proposed solution (with only 3 active surfaces), but its advantage is only a factor  $\sim 1.3$  in a LEO. In fact the local zenith cut removes about 40% of the events in the regular cube case, and about 12% in our configuration. These removed events can still be considered valuable for calibration<sup>2</sup> so we think that our geometry provides a more reasonable ratio of diagnostic/science datasets.

From this simulation, we can also study the acceptance as function of the polar coordinates  $\theta - \phi$  in the detector reference frame, in order to study the uniformity of the field of view. Figure 3 shows an histogram of the number good events (thus proportional to the acceptance) as function of  $\theta - \phi$ . We can see that the field of view is not completely uniform, the 3 active surfaces are clearly visible at  $\phi = 90^\circ, 210^\circ$ , and  $330^\circ$  in this reference system. The asymmetry is about 15% and does not depend on the cube side  $L$ .

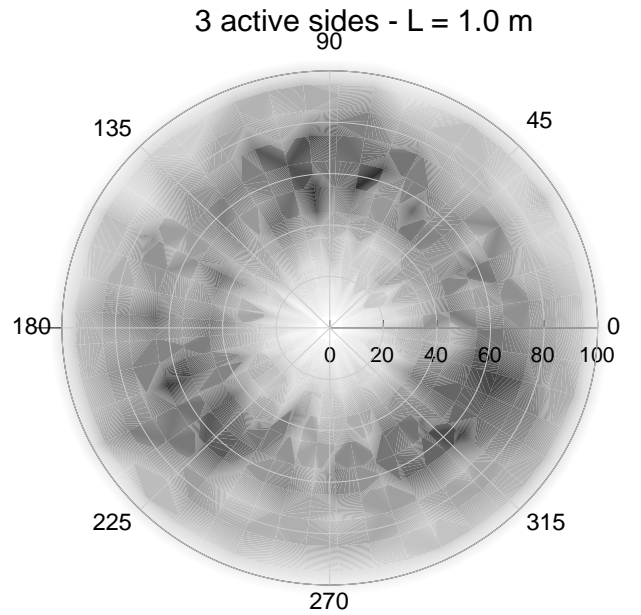


Figure 3: Polar plot of the acceptance as function of spherical coordinate  $\theta - \phi$  in the detector reference frame. The intensity of the color is proportional to the acceptance in that direction. Here only the case  $L=1 \text{ m}$  is plotted to show the asymmetry (about 15%) due to the orientation of the 3 active surfaces of the proposed geometry.

<sup>2</sup>As an example, events from the Earth's limb are a source of high energy  $\gamma$ -rays useful for on orbit check of electromagnetic response.

#### 4. Simulation of a simple implementation

The exercise in the previous section involves only a simple cubic geometry, and does not include any details on the detector elements. However to be able to estimate performance like angular and energy resolution for both electron and hadrons, we need to take a further step and make a more detailed simulation of the detector. This implies making some decisions on the detector element technology and detailed geometry (size and length). Moreover, some event reconstruction algorithm must be introduced, in order to take advantage of the three dimensional sampling of the shower development.

The details of the technology and algorithm can significantly change the performance of the instrument. In this work we don't want to propose a specific detector layout, nor to optimize the detector parameters for specific requirements or to implement a full simulation, including e.g. detailed sensor behavior. We just want to provide an idea of the expected performance, to be further studied and optimized in future works, taking also into account available technology and laboratory tests. We implemented a simple simulation of a possible detector configuration, based on Geant4 toolkit [7], and we will show the results of a few tests with electron and proton beams, using a very simple shower reconstruction.

In this exercise we implemented a sampling calorimeter with copper as absorber material (atomic number 29, density  $8.960 \text{ g/cm}^3$ )<sup>3</sup> and scintillating fibers to sample the energy. We also included clear fibers to sample the Cherenkov light and to provide a further set of information for protons. This choice of material roughly follows the one done by the RD52 [8] proposal for their hadronic calorimeter. The basic element is a bar 80 cm long and 2 cm wide. The bars are assembled in a regular grid having  $20 \times 20$  readout elements in each of the 3 faces. See figure 1 for a sketch of a  $3 \times 3$  matrix. In each bar the sampling is done with a grid of  $13 \times 13$  fibers of 1 mm diameters, alternating scintillating and clear fibers as in figure 4. Scintillating fibers are made of Polystyrene (density  $1.05 \text{ g/cm}^3$ ) with a 0.01 mm thin layer of PMMA cladding (density  $1.19 \text{ g/cm}^3$ ), the clear fibers have a core of PMMA (index of refraction 1.49) with fluorinated polymer as cladding (index of refraction 1.42). We chose to limit the bar length to 80 cm to avoid a too computing intensive simulation, and to keep it closer to the dimensions of a feasible prototype for laboratory tests. The mass of the calorimeter (including fibers and empty spaces) can be estimated in about 2.44 tons, with an average density of  $4.77 \text{ g/cm}^3$ , not far from CsI one. By choosing titanium instead of copper, as passive material, the average density becomes  $2.6 \text{ g/cm}^3$ , and even a cube of  $L=1.5 \text{ m}$  would lead to a reasonable mass of about 9 tons. Table 1 summarise a few example of possible material choice.

The simulation saves the energy in the scintillating fibers in each bar, the “S” signal in the rest of this work, and number of Cherenkov photons in clear fibers, the “C” signal. There is

Material	$X_0$ [cm]	$L_{int}$ [cm]	$\langle \rho \rangle$ [g/cm <sup>3</sup> ]	$M_{80}$ [t]	$M_{150}$ [t]
Titanium	3.56	27.80	2.6	1.3	8.8
Iron	1.76	16.8	4.2	2.2	14.2
Copper	1.44	15.32	4.77	2.44	16.1
Lead	0.56	17.6	6.0	3.0	20

Table 1: Comparison of a few absorber materials: radiation length  $X_0$  and nuclear interaction length  $L_{int}$  of each material are shown together with the resulting average density  $\langle \rho \rangle$  of the detector. For completeness we show also the total mass for a cube of 80 cm ( $M_{80}$ ) as in used setup, and of 150 cm ( $M_{150}$ ) the largest considered in section 3. It is worth noticing that commercially available materials are usually alloys, but their properties are not far from the main element.

no attempt to simulate a readout system, like electronic and/or detector gain and noise.

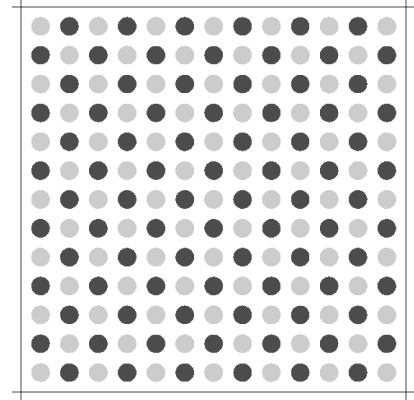


Figure 4: Cross section of a calorimeter bars that shows the layout of the scintillating (dark gray) and clear fibers (light gray).

We simulated a beam of electron and protons with  $1/E$  spectrum from 20 GeV to 5 TeV. The particles enters from one side of the detector with small incidence angle (up to  $10^\circ$ ). We used version 10.0-patch-04 of the Geant4 toolkit with the standard FTFP\_BERT physics and optical photon generation turned on. Since the propagation of optical photon is very computing intensive, we killed Cherenkov photons tracks after generation and check their angle with respect to fiber direction to evaluate if they undergo internal reflection (in this case we consider the photon as collected in the sensor) or not. This solution permits to run a reasonable number of events with the available computing resources.

The reconstruction of particle direction is done in a very simple way, plotting the distribution of the S and C signal in the two lateral view (with respect to the beam direction), and fitting with a straight line the two histograms. The fit slopes in the two directions are converted to coordinates in the detector reference frame and compared to the incoming particle direction. In detail, the beam enters from the  $+Y$  surface, therefore the  $XY$  and  $ZY$  projections (which correspond respectively to bars along the  $Z$  and along the  $X$  direction) represent the two lateral views. The fit is done separately for S and C signal, so for each event, we have two direction estimates. Figure 5 shows

<sup>3</sup> [http://pdg.lbl.gov/2015/AtomicNuclearProperties/HTML/copper\\_Cu.html](http://pdg.lbl.gov/2015/AtomicNuclearProperties/HTML/copper_Cu.html)

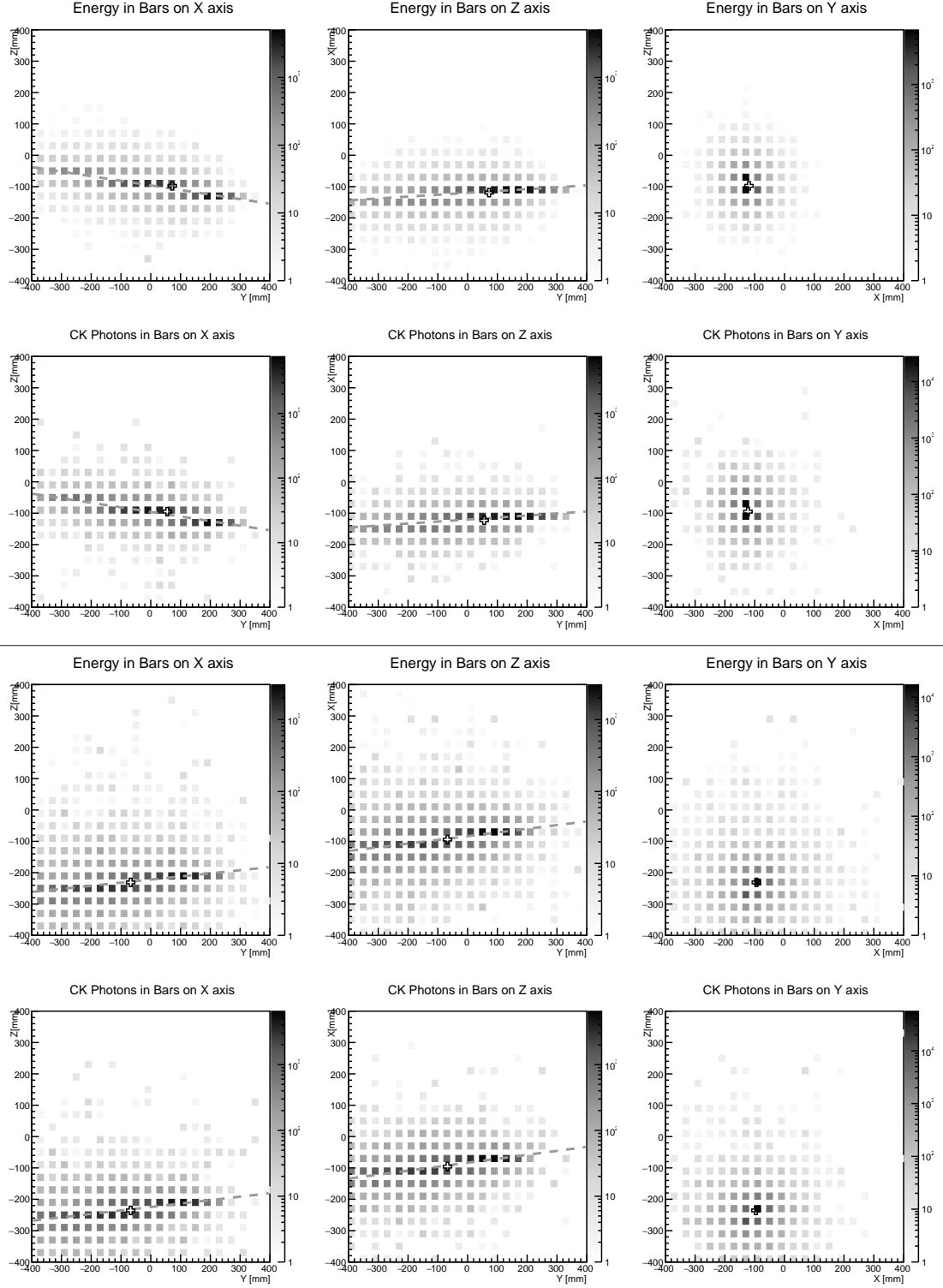


Figure 5: Example of how a high-energy event looks like in this simulation: distribution of S and C signals, for a single 2 TeV electron (top 2 rows) and 5 TeV proton (bottom 2 rows). The baricenter of the signals is shown with a cross, while the fits in the 2 lateral sides are shown with gray dashed line.

an example of this reconstruction for one event.

To evaluate performance on particle direction we calculated the angle between true and reconstructed direction (Point Spread Function, PSF). The angular resolution is evaluated as the angle that contains 68% or 95% of the events. The results are shown in figure 6 for S signal only, since the C signal was found to be almost equivalent and provides the same angular resolution, for both electron and proton and in the whole energy range. For electrons we see that the 95% containment is quite close to the 68% one, indicating a compact distribution with small tail. The energy dependence is also small, the typical resolution is  $\sim 2^\circ$ . For protons the tail is larger, increasing the value of the 95% containment, and there is also a larger energy dependence with the PSF improving with energy. Even if it can be considered adequate for most of the high-energy cosmic-ray science topic, it can be improved with a more clever reconstruction and optimized design. As an example, each bar can be further subdivided in sectors and read out with different devices to improve the granularity.

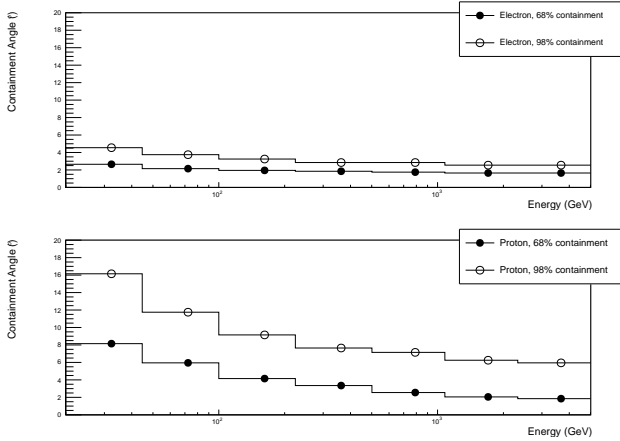


Figure 6: Angular resolution (defined as 68% and 95% containment of true-reconstructed angle distribution) as function of energy, for electrons and protons.

Particle energy is evaluated differently for electrons and protons, since the two particle behaves very differently in the detector. Electrons have a very compact shower that is fully absorbed in this detector. Therefore the instrument works as total absorption calorimeter in this range and the energy can be easily reconstructed by the sum of the S signal multiplied with a single calibration constant. The resulting energy resolution can easily be as low as few percent, and we won't discuss it further.

Proton energy reconstruction is more complex: hadronic shower is quite broad and starts later than the electromagnetic one. The S and C signal baricenter distribution spans about the second half of the calorimeter depth, and has small, but clear energy dependence. As a consequence about half of the proton energy is lost outside the detector. The simple reconstruction algorithm implemented here uses the sum of S and C signal with a single calibration constant each, without trying to use shower shape information. A small correction on the shower depth (the energy baricenter) is applied to the S sum, and the

two signals are averaged together. The only event selection is to remove MIPs by requiring a minimum energy in the S signal empirically set to 100 MeV. We studied the energy dispersion of this algorithm, defined as the reconstructed energy divided by the true energy. As expected it peaks at around 1 and has a larger tail on the left side. Figure 7 shows an example with all the events above 1 TeV. The energy resolution is defined as the half-width of smallest window that contains 68% of the events (corresponding to  $1\sigma$  in the gaussian case). We found that we can achieve a value around 30–25% in this energy range (with small energy dependency). A value that is close to the one expected in the next generation instruments and that can be improved with a more complex algorithm and detector optimization, e.g. by a more careful selection of the passive material in terms of density, radiation length and interaction length.

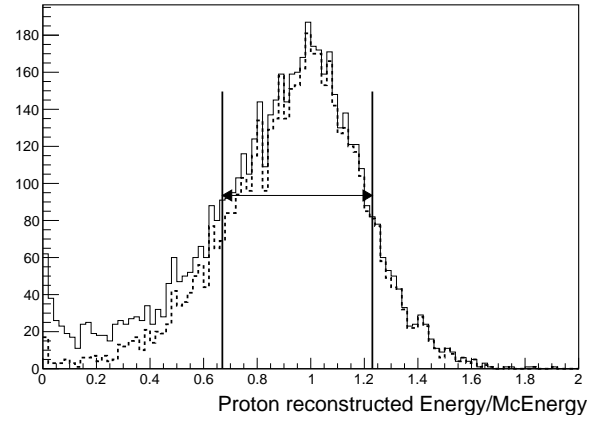


Figure 7: Energy dispersion (reconstructed energy/true energy) for protons above 1 TeV. The arrow and the vertical lines show the windows that contains 68% of the events, half of its width (the energy resolution) is about 28%. The dashed-line histogram represent the same distribution with a cut on C/S ratio for a slightly better resolution of about 24%.

In this work we exploited the dual readout only for proton energy reconstruction, but there are several other advantages of this technique. As an example, it has been shown that the ratio between C and S signal carry information on the electromagnetic fraction of the shower [9]. It can help to study the quality of the energy reconstruction and select events with good resolution in case it is important for specific science topics. We can slightly improve the resolution with a cut on a the C/S signal ratio reducing the left-side tail of the distribution (dashed line in figure 7). It can also be used for electron/hadron separation, together with other shower topology information like its transverse size. All these capabilities require a more advanced event reconstruction, in particular in a complex geometry as the one we are proposing, for this reason we will not discuss them in details.

## 5. Conclusions

In this work we made a first description of a new detector for cosmic-ray study in orbit. The main idea is to have a modular

detector that can scale up to a large size by keeping a good granularity and a relatively small number of channels. The implementation is done with detector elements that can be oriented along the 3 Cartesian axes and intersected in a way that provides three-dimensional sampling to particle showers.

We tested this idea with simple simulations to make sure the concept works and to evaluate its performance in a realistic, although simplified, setup. We found that we can achieve an acceptance of a few  $\text{m}^2 \text{sr}$  with a lateral size of the order of 1 m, even including the requirement of Earth-limited field of view. This is important since heavy satellites required by this kind of science will likely be placed in Low Earth Orbits, where this condition holds. We showed that angular resolution of a few degrees is feasible and there is room for improvements. We found that it can work not only as electrons, but also as protons telescope with good performance, with energy resolution down to  $\sim 25\%$ .

Of course this work has to be considered as preliminary with some limitations that we also discussed: the lack of sensor description in the simulation, the very simple event reconstruction etc. Other steps are necessary to move from an ideal concept to a feasible detector, the most important would be to improve the simulation by implementing the missing parts and validate the concept with a detector prototype to be tested with real beam lines.

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